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Measurement of light polarization characteristics from an oil-polluted soil surface in near-infrared bands

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Oil pollution can be monitored by infrared remote sensing technology. In this work, the degree of polarization (DOP) was established as a quantitative index of oil pollution. The crude oil and the local typical surface soil from the Songyuan oil field in Jilin province were collected. Some soil samples with four levels of oil content and three levels of water content were prepared and measured. The DOP of the polluted soil and the clean soil in the field was also measured at 180° relative viewing azimuth angle, and 10°, 30° and 50° viewing zenith angles. It was found that with rising soil oil content, the DOP of the reflected light on the soil surface increased when the soil water content was low, and decreased when the soil water content was high.

oil pollution of soil, polarization remote sensing, degree of polarization

Oil pollution of soil is a concern for all governments. Developed countries have invested heavily to establish oil pollution detection systems[1]. By measuring the location, the spill volume and the spreading trend, oil pollution can be monitored. Current remote sensing monitor systems use visible light, infrared and UV optics, microwave radiometry, lasers and fluorescence[1−7]. Infrared measurement is generally considered the most practical method[1]. The pollution is determined by the differences between the polluted areas and the surrounding areas in the near-infrared band on the spectrum.

With the progress in bidirectional reflection, the multi-angle polarized light remote sensing developed gradually in the end of the 1970s[8]. Suits et al. developed the bidirectional reflection distribution function (BRDF) to retrieve the spatial structure of target ground objects[9−13]. The remote sensing systems of ground objects based on bidirectional reflection were established successfully at the beginning of the 1990s. Light polarization was found to possess key information on the target radiation[7]. The ground objects can generate polarized light in the reflection, diffusion and transmission of electromagnetic radiation, either on the ground or in the atmosphere. The polarized light thus provides a new means of remote sensing. Through many experiments on the space shuttle, the polarization was proven superior in soil plant classification, atmospheric aerosol detection, and seawater surface status analysis[7,14]. Currently, the accessible data of satellite polarization remote sensing mainly comes from the POLDER carried out by ADEOS launched by CNES of France in 1996. The POLDER has eight channels, three of which are for the measurement of polarization. These three channels can observe the same target from 13 different viewing angles. For each viewing angle, the target is profiled in eight narrow wave bands of spectrum. The three channels are located at three different angles of polarization. The instrument

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can obtain the bidirectional reflection distribution function (BRDF) and the bidirectional polarization distribution function (BPDF).

Nevertheless, light polarization remote sensing is still at the stage of model verification at present, and the in-field applications are still rare. Millard et al.[15] proposed to monitor oil pollution in water body by light polarization. Curran suggested the use of light polarization in vegetation classification[16] and biomass density estimation[17]. Curran[18] also demonstrated the quantitative relationship between the soil water content and the polarization degree of the reflected light in certain cases. Zhao et al.[8] investigated the light polarization on leaf moist soil[19] and waters[20], and found that the polarized reflection ratio of the ground object was highly dependent on the object's nature, wave band, polarized angle, incident zenith angle, detecting zenith angle and the relative detecting azimuth angle (the angle between the incident azimuth angle and detecting azimuth angle). These factors were also found to significantly affect the polarization reflection ratio of rocks[21,22]. On the basis of Stokes parameters, Zhao et al.[23] applied the Malus law to establish the quantitative relationship between the multi-angle polarization and the bidirectional reflection of the oil spill on water surface. Through the measurement of the polarized reflection of different soil, Song et al.[24] suggested that the polarized reflection might occur on the soil surface when the soil water content reached a certain level. Previous researches have shown that the polarization is dependent on both the water content and the oil content of the soil. In this work, the polarization degree was established as a quantitative indicator in remote sensing, and the polarized light spectrum of soil with different water and oil contents were measured in the near-infrared band. This work will lay a foundation for the future application of polarized remote sensing to the monitoring of oil pollution in soil.

1 Experimental

1.1 Specimen collection and treatment

The crude oil was collected at the Songyuan oil field in Jilin Province. The polluted soil was collected near the oil well (sampling depth < 20 cm), and the clean soil was collected nearby as the reference. The soil type was saline meadow. The water and oil contents of the soil specimen were measured before the specimen was air-dried to constant weight. The impurities were then removed, and the soil was picked up on a 180# sieve and stored at 4℃ before use.

1.2 Experiment design

Soil samples with different water and oil contents were prepared by adding a specific amount of distilled water and crude oil to the dry soil. The crude oil was dissolved in chloroform before adding into the soil. The light components and chloroform were removed by evaporation with moderate heating to get the oil-containing soil sample[14]. The water content levels were 0.0%, 12.5% and 20.0%, and the oil content levels were 0.0%, 7.5%, 12.5% and 20.0%, respectively. 4 times of repetitions are arranged for each of the above specimen.

The degree of polarization was established as the quantitative indicator and calculated by

$$P = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{I_{90} - I_0}{I_{90} + I_0}, \tag{1}$$

where I_{90} is the polarization reflection ratio when the polarizer photic axis is perpendicular to the light incidence plane, and I_0 is the polarization reflection ratio when the polarizer photic axis is parallel to the light incidence plane. The degree of polarization calculated from eq. (1) is independent of sunlight intensity; Thus no reference board is needed[10,11].

1.3 Measurement

The polarized reflection of the soil sample was measured by a bidirectional reflection photometer (Changchun Research Institute for Optics Mechanics and Physics, CAS). The instrument was comprised of three major parts: a light source system, a bidirectional reflection photometer system and a control system. With the instrument we measured the reflection and radiation of ground objects in all directions from various observation points. The quick data collection and data processing were automatically completed by the electronic control board and the micro-computer. The data output was in the form of sheet or curve. Statistic analysis was also available. A nickel tungsten lamp was used as the light source to give the radiation at two wave bands: 630—690 nm and 760—1100 nm. In the range of 0°—70°, an incidence zenith angle of light source was taken at every 10°. Seven detecting heads from 0°—60° were set up on the detecting rack with a spacing of 10°. At each 10° from 0°—360° between the light source and the detector, a detecting direction (180° for mirror reflection) was established. The instrument was also equipped with polarization lens, which could rotate in any angle. The sample cell was a black rigid plastic box, 5.5 cm in diameter and 1.3 cm in depth. The geometrical light path is illustrated in Figure 1.

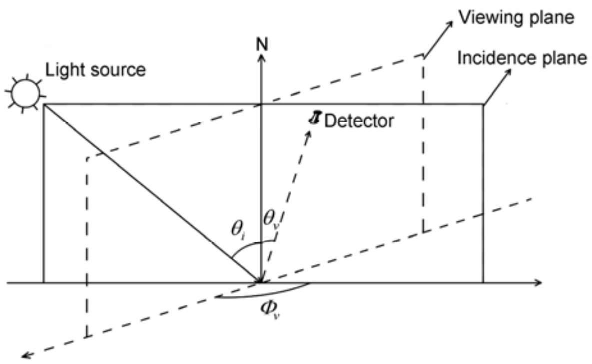

Figure 1 Measurement geometry. θ_i, incidence zenith angle; θ_v, viewing zenith angle; ϕ_v, relative azimuth angle.

The sample cell was evenly and compactly filled with the soil sample. A piece of ground glass was used to press the soil to the cover edge level and shave the soil surface before the polarized reflection was measured. Each final output was the mean value of 30 measurements on that photometer position.

The following series of experiments were carried out. (i) The polarization degree of reflected light of the dry soil with different oil content was measured at 30° and 10° incidence zenith angles, 180° relative detecting azimuth angle. (ii) The polarization degree of reflected light of the soil sample with 12.5% water content and different oil content was measured. (iii) The polarization degree of reflected light of the soil sample with 20.0% water content and different oil content was measured.

In the field experiment, the spectrum was measured by a USB 2000 high-resolution spectrometer (Ocean Optics), and the optical fiber was fixed on the modified theodolite to locate the detecting angles exactly. The experiment was performed at 10 a.m. of May 17, 2007, on No. 225 well in J13 district of the Songyuan oil field. It was cloudless sunny and there was a soft breeze. The polarization degrees of reflected light of the polluted soil and the nearby unpolluted soil were measured at 180° relative detecting azimuth angle, and 10°, 30° and 50° detecting zenith angles.

2 Results and discussions

2.1 Results

The polarization degree values measured in the lab at 50° incidence zenith angle, different detecting zenith angles and 0°—360° relative detecting azimuth angle are illustrated in Figures 2—4. In the mirror reflection direction (180° relative detecting azimuth angle), the polarization degree of reflected light exhibited a peak value. The peak value was 0 when the oil content was 0.0%, and increased with rising oil content. The polarization degree values at 30° and 10° incidence zenith angles, 180° relative detecting azimuth angle are shown in Tables 1 and 2. At a small incidence zenith angle, the polarization degree of reflected light increased along with a rise in the oil content in the direction of specular reflection. At the same oil content, the polarization degree in the direction of specular reflection increased with a rise in the incidence zenith angle and the detecting zenith angle (Figures 2—4).

The polarization degrees at 180° relative detecting azimuth angle with an identical incidence zenith angle and detecting zenith angle are presented in Table 3. It was found that when the soil was not dry, the polarized reflection could be observed even at zero oil pollution. The polarization degree of reflected light on the soil surface increased with increasing oil content.

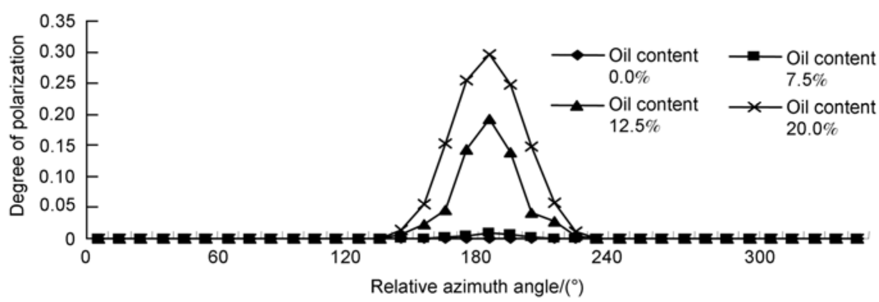

Figure 2 The polarization degree of reflected light of the soil with 0.0% water content at 50° incidence zenith angle and 50° viewing zenith angle.

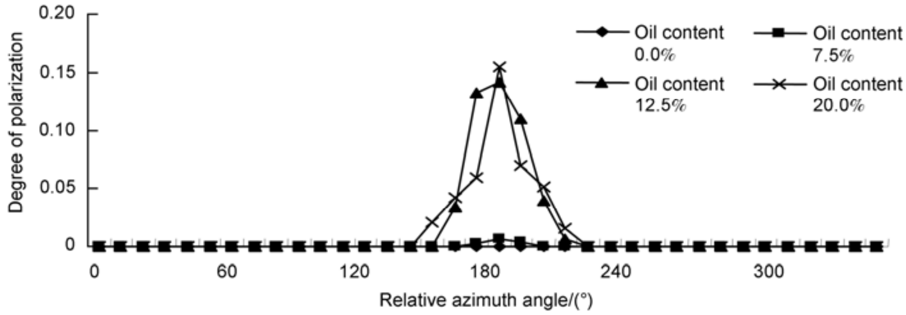

Figure 3 The polarization degree of reflected light of the soil with 0.0% water content at 50° incidence zenith angle and 30°viewing zenith angle.

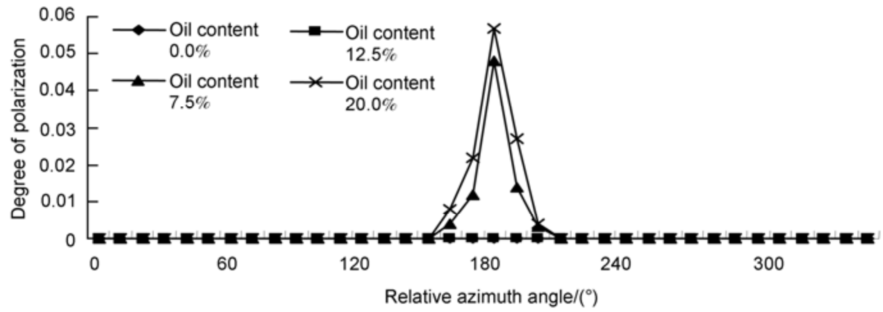

Figure 4 The polarization degree of reflected light of the soil with 0.0% water content at 50° incidence zenith angle and 10° viewing zenith angle.

Table 1 The polarization degree of reflected light of the soil with 0.0% water content at 30° incidence angle and 180° relative azimuth angle

Viewing zenith angle	Oil content (%)			
	0.0	7.5	12.5	20.0
10°	0.000	0.000	0.008	0.030
20°	0.000	0.000	0.033	0.045
30°	0.000	0.000	0.056	0.076
40°	0.000	0.005	0.089	0.114
50°	0.000	0.010	0.129	0.187
60°	0.000	0.013	0.141	0.219

Table 2 The polarization degree of reflected light of the soil with 0.0% water content at 10° incidence angle and 180° relative azimuth angle

Viewing zenith angle	Oil content (%)			
	0.0	7.5	12.5	20.0
10°	0.000	0.000	0.000	0.005
20°	0.000	0.000	0.007	0.017
30°	0.000	0.000	0.012	0.020
40°	0.000	0.000	0.022	0.036
50°	0.000	0.000	0.045	0.051
60°	0.000	0.000	0.052	0.057

The polarization degree at 180° relative detecting azimuth angle with an identical incidence zenith angle and detecting zenith angle is presented in Table 4. Strong polarized reflection was observed on the unpolluted soil with high water content. The polarization de-

Table 3 The polarization degree of reflected light of the soil with 12.5% water content at 180° relative azimuth angle and identical incidence and viewing angles

Viewing zenith angle	Oil content (%)			
	0.0	7.5	12.5	20.0
10°	0.002	0.006	0.023	0.051
30°	0.016	0.035	0.079	0.098
50°	0.074	0.135	0.143	0.152

Table 4 The polarization degree of reflected light of the soil with 20.0% water content at 180° relative azimuth angle and identical incidence and viewing angles

Viewing zenith angle	Oil content (%)			
	0.0	7.5	12.5	20.0
10°	0.070	0.013	0.012	0.015
30°	0.116	0.033	0.036	0.039
50°	0.320	0.245	0.231	0.234

gree of reflected light on the soil surface declined drastically with the introduction of oil pollution. The oil content level appeared to have little effect on the polarization degree.

The field observations are summarized in Table 5. The oil and water content of the polluted soil were 8.7% and 5.1% respectively, and the water content of the clean soil was 4.7%.Table 5 shows that polarized reflection was not observable on the surface of clean soil, and oc-

Table 5 The polarization degree of reflected light at 180° relative detecting azimuth angle in the field measurement

Viewing zenith angle	Wave band (mm)	Non-polluted soil	Polluted soil
10°	799—801	0.000	0.005
	819—821	0.000	0.004
	839—841	0.000	0.004
30°	799—801	0.000	0.021
	819—821	0.000	0.014
	839—841	0.000	0.011
50°	799—801	0.000	0.087
	819—821	0.000	0.064
	839—841	0.000	0.042

curred partially on the polluted soil. The reflected light was partially polarized light including natural light and linear polarized light.

2.2 Discussions

Previous researches have proven that, according to the Fresnel reflection and refraction principle[25,26], the polarization in the reflected light is generated by the specular reflection on the soil surface[15,18]. With parallel incidence light on the surface of the unpolluted dry soil, diffuse reflection occurred on the soil surface, and the reflected light was completely natural light. The dry soil was loose and had a rough surface. With the addition of water, the soil particles would attract water as a result of the Van Der Waals force and hydrogen bonding. The scattered soil agglomerates absorbed water to increase the viscidity between particles, and the soil surface became smoother to allow partial mirror reflection. Consequently, the reflected light was consisted partly of polarized light[18]. The introduction of oil at this point led to an increase in polarization of the reflected light because the oil molecule enwrapped the soil particles and lubricated the particle surface to give better mirror reflection. At higher water content, the soil particles as well as the gaps between them were saturated with water. The soil surface was neat and smooth, and had high viscosity. The introduction of oil at this point reduced the polarization of the reflected light because the repellence between oil and water magnified the gap between soil agglomerates and broke the mirror reflection on the surface.

Under natural conditions, water in the topsoil mainly comes from atmospheric precipitation. After each precipitation, the unpolluted soil will be saturated and all gaps will be filled with water. Through evaporation, water is removed from the topsoil, and the large gaps in the soil structure become blank. The soil agglomerates and then breaks into scattered small masses as the binding force is lost after dehydration. Water in the gaps between the soil particles is replaced by air, and the particle surface is dry and loose. Therefore, in sunny weather, although the unpolluted soil has a certain water content, it is still the diffuse reflection instead of the mirror reflection that occurs on the soil surface, as the water content is actually rather low. In the polluted soil, water is kept tightly in the soil by the oil after precipitation, and the complete soil agglomerate structure remains. Water evaporation is little even under strong irradiation in the sunny weather. The topsoil enwrapped by the oil film exhibits enhanced polarization in reflection.

The degree of oil pollution in the soil can be quantitatively monitored by the polarization degree of reflected light in the near-infrared band. At low soil water content, the polarization is zero for clean soil and will increase with rising pollution degree. At high soil water content, the polarization decreases with rising pollution degree. The distinction between "low" and "high" soil water content is dependent on soil type, content of organic matter, mechanical compositions, etc[24,27]. The research on the determination of the distinction is currently underway.

3 Conclusion

The oil pollution of soil can be remotely and quantitatively monitored by the polarization degree of reflected light in the near-infrared band at 180° relative detecting azimuth angle. With rising soil oil content, the polarization degree of the reflected light on the soil surface increases when the soil water content is low, and decreases when the soil water content is high. In addition, at the same soil water and oil content level, greater the incidence zenith angle and detecting zenith angle, the higher the degree of water content. Therefore, a greater detecting zenith angle gives a lower detection limit.

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